REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY) March 2013	**2. REPORT TYPE** Viewgraph	**3. DATES COVERED** (From - To) March 2013- May 2013

4. TITLE AND SUBTITLE
X-ray Radiography Measurements of Shear Coaxial Rocket Injectors

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A. Kastengren, A. Schumaker, M. Lightfoot, S. Danczyk, & R. Bernstein

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q0X3

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQRC
10 E. Saturn Blvd.
Edwards AFB CA 93524-7680

8. PERFORMING ORGANIZATION REPORT NO.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-VG-2013-082

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A: Approved for Public Release; Distribution Unlimited. PA#13214

13. SUPPLEMENTARY NOTES
Viewgraph for the 2013 ILASS Americas, Pittsburgh, PA, 7 May 2013.

14. ABSTRACT
Shear coaxial injectors are a common injector type for liquid-rocket-propulsion applications and can be found in many oxygen/hydrogen engines. These injectors rely on the shear between an outer lower-density, high-velocity annulus and a higher-density, low-velocity inner jet to atomize and mix the propellants. Because of the dense-jet core, the optical densities of these sprays are high, particularly near the injector where primary atomization and flame holding take place. The large optical density has prevented interrogation, detailed study, and understanding of this important region. The evolution of x-ray radiography techniques using intense x-ray sources (such as Argonne National Laboratory's Advanced Photon Source) has allowed the measurement of quantitative equivalent path lengths and projected densities in the near-injector regions of shear coaxial injectors. Using water and gaseous nitro-gen as propellant simulants at atmospheric backpressure, the effect of momentum flux ratio and mass flux ratio, are investigated for three injector geometries operating at momentum flux ratios spanning the range from 0.5 to 15.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Stephen Schumaker
a. REPORT **Unclassified**	**b. ABSTRACT** **Unclassified**	**c. THIS PAGE** **Unclassified**	SAR	20	**19b. TELEPHONE NO** (include area code) 661-525-5165

X-Ray Radiography Measurements of Shear Coaxial Rocket Injectors

Alan Kastengren

Advanced Photon Source, Argonne National Laboratory

Argonne, IL

Alex Schumaker, Malissa Lightfoot, Steve Danczyk, & Robert Bernstein

Rocket Propulsion Division, Air Force Research Laboratory

Edwards AFB, CA

Motivation

- Shear coaxial jets have been investigated for over sixty years but quantitative measurements in the near-field of these two-phase jets is lacking
  - Investigate the effect of momentum flux ratio, mass flux ratio and post thickness on the liquid mass distribution
  - Use quantitative centerline profiles to define atomization regions
- Near-field region of shear coaxial sprays is virtually impenetrable to visible light, severely limiting optical diagnostics
- X-ray radiography has developed over the past 12 years from a proof-of-concept measurement to a well-developed diagnostic technique
  - Used to study diesel, swirl, gas-centered swirl-coaxial, impingers, and aerated liquid jet injectors
- Use a monochromatic beam of x-rays at a synchrotron x-ray source to probe spray flowfield
  - Main interaction is absorption, not scattering
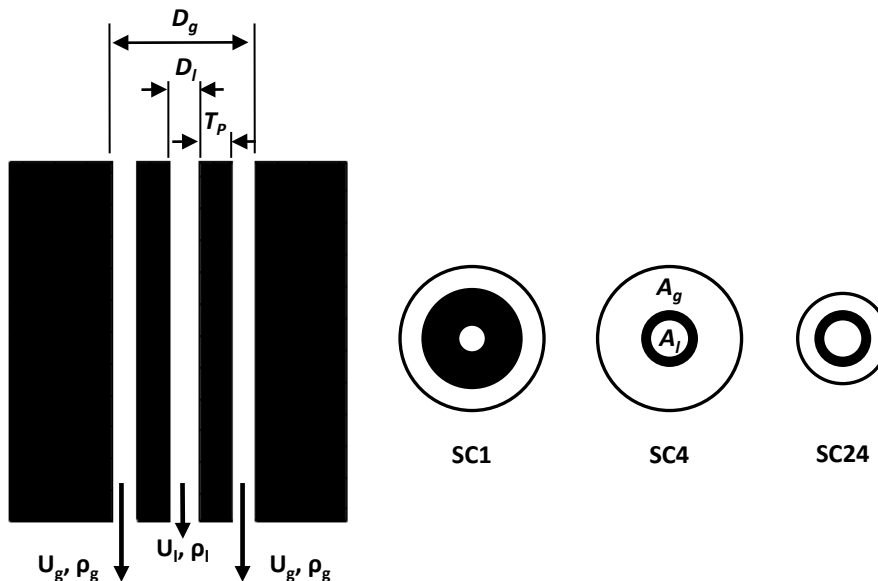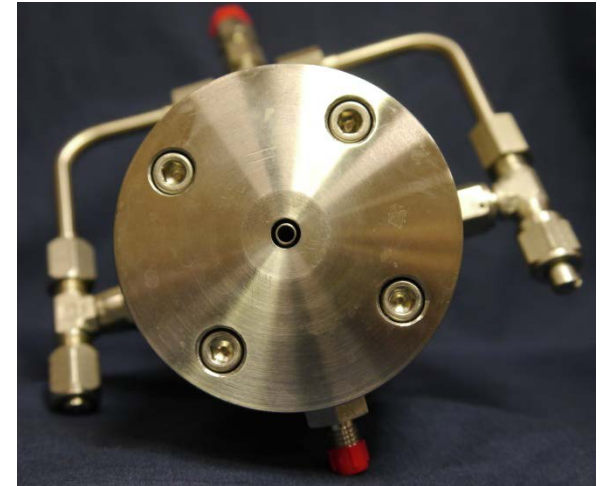 - Mass based: insensitive to fluid-gas interfaces

Shear Coaxial Injectors

- Shear coaxial jets can be found in a number of combustion devices
  - Turbofan engine exhaust, air blast furnaces, and liquid rocket engines
- Substantial fundamental research exists on single phase coaxial jets
  - Quantitative mass distributions measured using PLIF and anemometry
  - Includes the case where both fluids are supercritical
  - Common in modern boost-class liquid rocket engines
- Current focus is on two-phase coaxial jets for rocket engine applications
  - Common in upper-stage engines and during throttled conditions, startup and shutdown transients of boost-class engines
  - Previous scaling efforts have been largely based on imaging of the liquid core
- Gaseous high speed outer jet (fuel) is used to fragment a dense liquid core (oxidizer)
  - Fuel is typically H_2 or CH_4 and oxidizer is LOX
  - For the current study liquid H_2O and gaseous N_2 are used as surrogates for oxidizer and fuel respectively
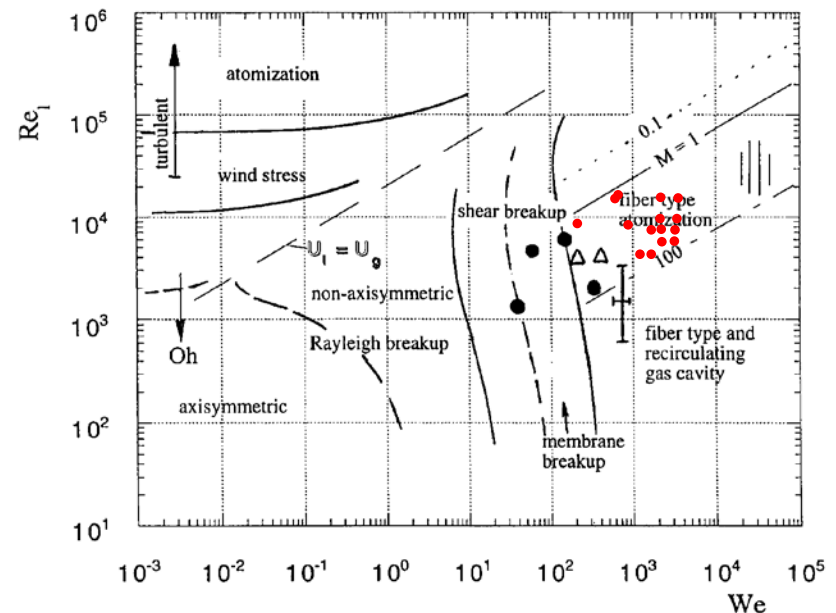
3

Injector Geometries

- Three injector geometries were used
  - SC4 & SC24 have the same inner jet geometry (D_l & T_p) but different area ratios
  - SC1 has a similar area ratio to SC4 but has a thickened injector post
- Injector was tested in a horizontal configuration
  - Injector face is sloped away from the center jet

SC1   SC4   SC24

Injector	D_l (mm)	D_g (mm)	T_p (mm)	L_l/D_l	A_g/A_l
SC1	2.08	10.2	2.32	48.8	13.4
SC4	2.79	10.2	0.457	36.4	11.5
SC24	2.79	6.35	0.457	36.4	3.40

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4

Controlling Parameters and Regimes

- Previous studies indicate two-phase coaxial jet atomization is controlled by 6 nondimensional parameters
  - Liquid and gas Reynolds number (*Re*), Ohnesorge number (*Oh*), Weber number (*We*), momentum flux ratio (*Φ*), and mass flux ratio (*m*)

  - *Φ* defined gas to liquid and *m* liquid to gas
- Test conditions all in the fiber type atomization regime (red points)
- Since test conditions are in the fiber type regime *Φ* and *m* are the controlling parameters
  - *Φ* controls primary atomization
  - *m* effects far field momentum transfer
  - Area ratio effects are accounted for in *m*

Regime Diagram: *Lasheras, J.C., and Hopfinger, E.J. Annual Review of Fluid Mechanics 32:275-308 (2000).*

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5

Test Matrix

- Test conditions based on 5 nominal Φ conditions (0.5, 2, 5, 10, & 15)
  - Gas velocities (U_g): 81-229 m/s, liquid velocities (U_l): 2.0-6.0 m/s
  - Weber #: 211-2260, Reynolds #: Gas: 8,900-52,000 & Liquid: 4,200-16,500
- SC4 and SC24 have the same inner jet geometry and use similar velocities at each Φ conditions, therefore, the 3.4 factor in m betweenSC4 and SC24 is due solely to the difference in area ratio
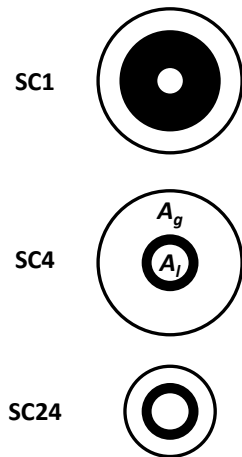
Condition	Φ	U_g (m/s)	U_l (m/s)	$\dot{m}_g$ (g/s)	$\dot{m}_l$ (g/s)	m	We	Re_g	Re_l
SC1-0.5	0.46	81	4.0	4.16	13.6	3.27	211	8,920	8,370
SC1-2	1.9	162	4.0	8.53	13.6	1.59	872	18,800	8,260
SC1-5	4.8	220	3.5	12.0	11.8	0.98	1667	27,600	7,290
SC1-10	9.6	182	2.0	9.62	6.79	0.71	1100	21,400	4,210
SC1-15	14	219	2.0	12.0	6.79	0.57	1651	27,300	4,240
SC4-0.5	0.49	125	6.0	9.85	36.7	3.72	673	25,800	15,700
SC4-2	2.0	229	5.5	18.4	33.6	1.82	2310	50,600	14,500
SC4-5	4.8	224	3.5	18.5	21.4	1.16	2260	51,800	9,150
SC4-10	9.1	219	2.5	18.4	15.4	0.84	2200	52,000	7,050
SC4-15	15	224	2.0	18.4	12.0	0.65	2250	51,400	5,590
SC24-0.5	0.46	120	6.0	2.88	36.7	12.7	635	10,400	16,500
SC24-2	1.8	212	5.6	5.40	34.3	6.34	2104	20,100	16,000
SC24-5	4.6	210	3.5	5.51	21.4	3.88	2120	21,000	9,340
SC24-10	8.7	211	2.5	5.44	15.4	2.83	2110	20,400	7,310
SC24-15	15	213	2.0	5.48	11.9	2.18	2140	20,700	5,550

SC1

A_g

A_l

SC4

SC24

Experimental Method

- Focused beam in raster-scan mode
  - 1D transverse scans at 8 location
  - Scans perpendicular to injector axis
- Beam size 7 x 8 μm FWHM
  - Beam Photon Energy: 10keV
- Each point averaged for 5 seconds
- Time resolved data taken simultaneously (not presented)
- Beer's law to convert x-ray transmission to mass/area in beam
- H_2O absorption coefficient at 10keV: 5.33 cm^2/g

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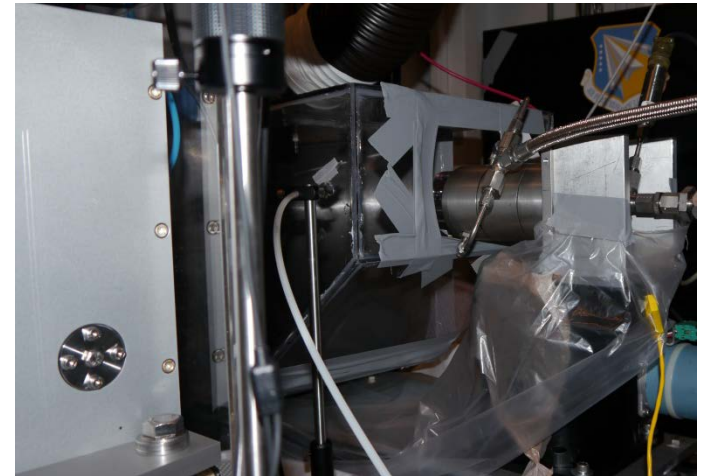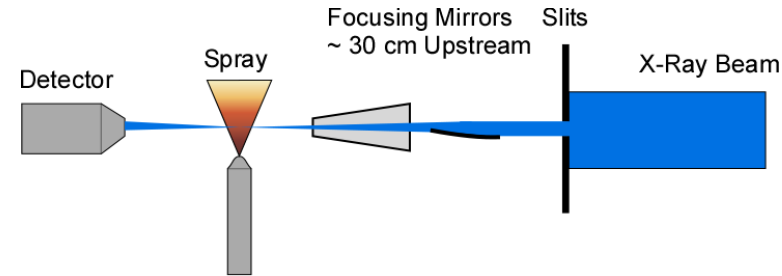
Mobile Flow Laboratory

- Self contained mobile system capable of delivering up to one kg/s of H2O and GN2 at pressures in excess of 200 atmospheres
  - Requires only power, LN2, and exhaust from the host facility
  - System fully rated to 408 atm (Allows more GN2 storage)
  - Dedicated Allen-Bradley control & Pacific Instruments data acquisition systems
  - Fully remote operation
  - High speed abort system on all data channels for added pressure safety
  - System is on wheels and can be assembled in under 2 days
  - Ran almost continuously (24 hours/day) for two weeks

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Radial EPL Profiles

- Near-injector EPL profiles have elliptical shape expected from a solid liquid jet
- EPL decreases as liquid core is atomized and droplets are accelerated
  - Atomization increases with increasing *Φ*
- Measurements where made 0.02 mm downstream capturing important details
  - Contracting of the liquid core (*Φ=0.5*)
 - 13% drop from 0.02 to 0.5 mm (*Φ=15*)

Φ=0.5

Φ =5.0

SC4
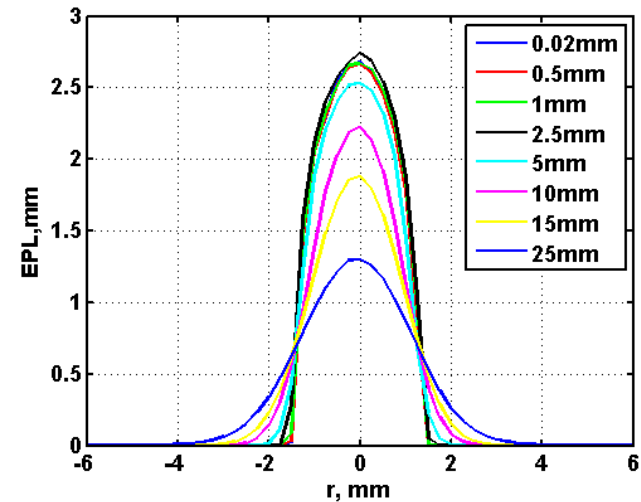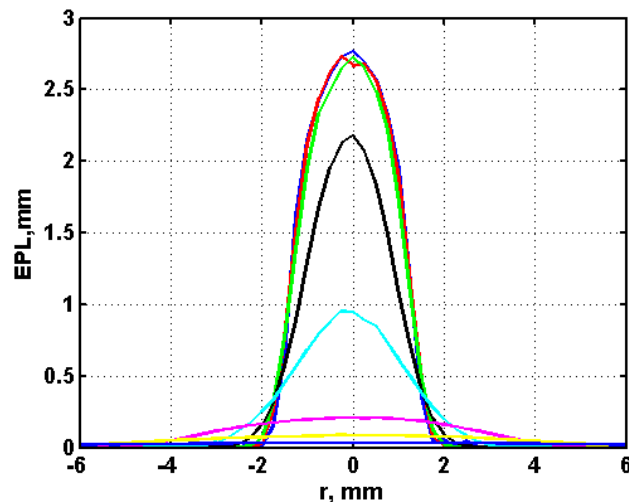
Φ =15
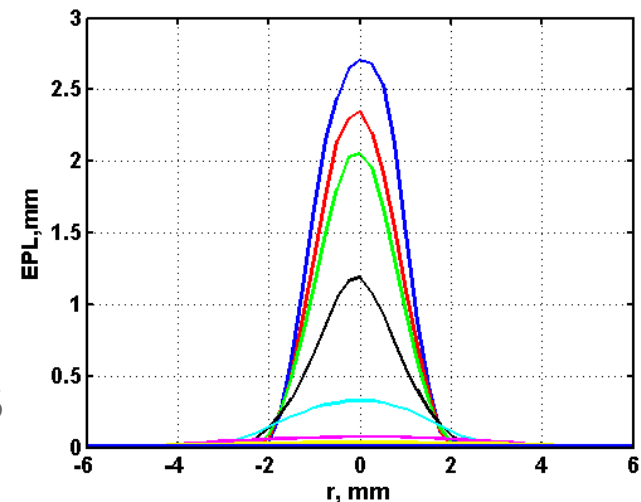
Momentum Flux Ratio

- Centerline EPL profiles shows same general trend reported in studies of the dark core length
  - Increasing Φ accelerates primary atomization, thus shorting the liquid core
  - The shorting of the primary atomization region is observable from the decrease in the initial slope of the centerline EPL profiles
  - Future work will look to relate EPL to dark core length
- Normalized centerline profiles show expansion and contraction of the liquid core at injector exit for low Φ values (0.49 & 2)

SC4
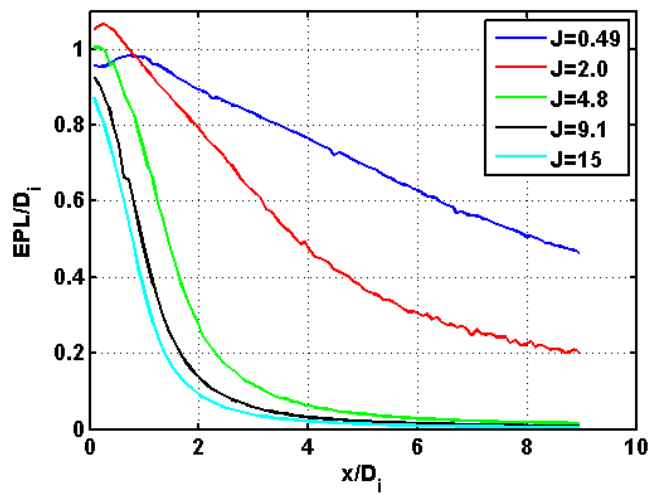
Centerline Profiles
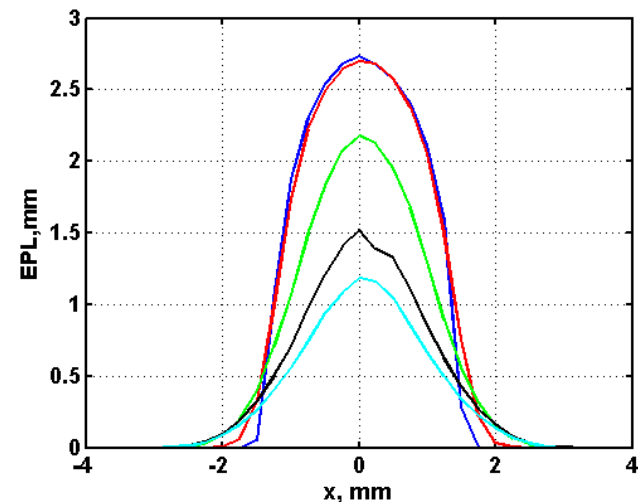
2.5 mm Downstream

Peak EPL Values

- For thin injector posts peak EPL was found to vary from D_i by up to 6%
  - Peak EPL's where found above and below D_i
  - $EPL/D_i > 1$: liquid in tip recirculation zone
  - $EPL/D_i < 1$: atomization, under resolved peak, & surface waves
  - Experimental error can contribute
- In general peak EPL decreases with increasing Φ
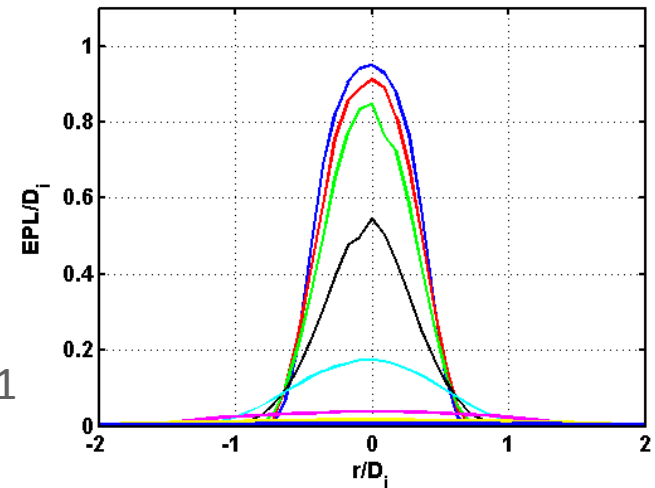 - Exceptions to this trend

Φ=2.0
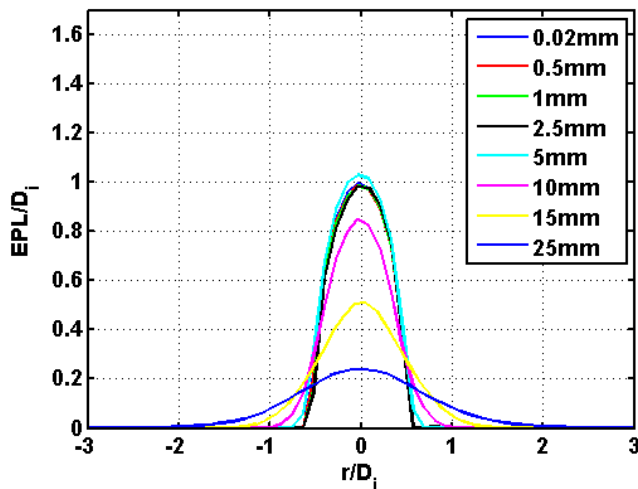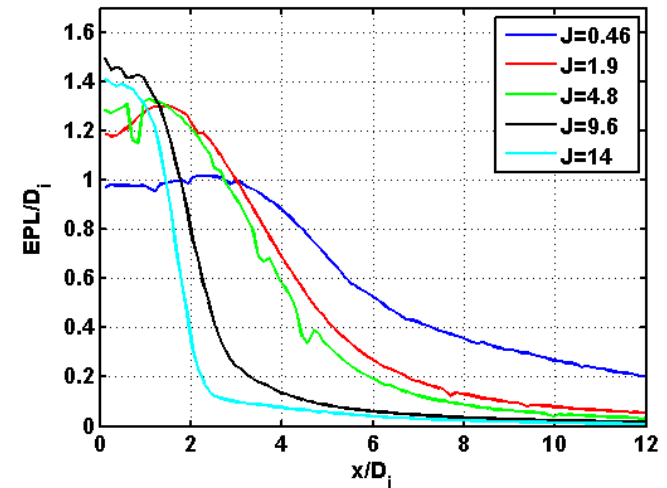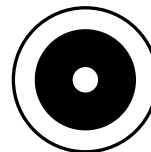
SC4

Φ =4.8
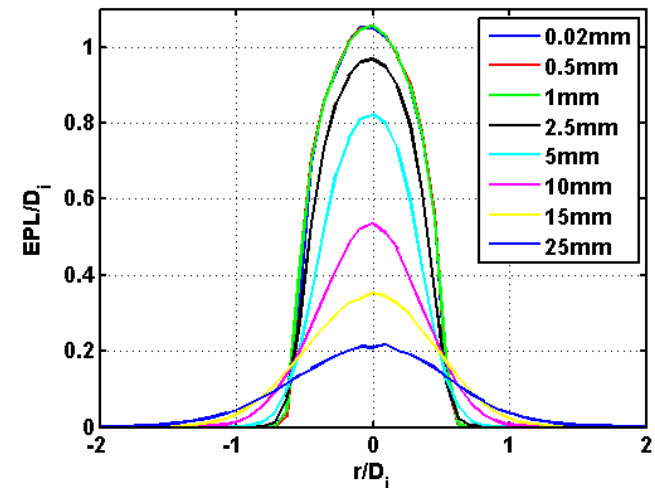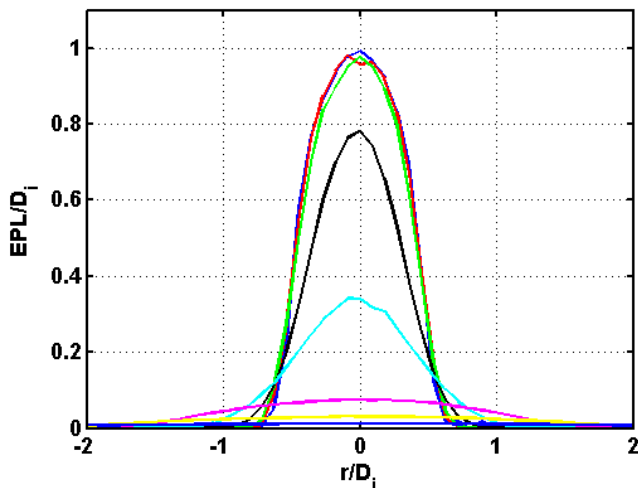
Φ =9.1

Injector Post Recirculation

- Normalized EPL can be well above 1 for injectors with a thick post
    - Tip recirculation zone contains a substantial amount of liquid
    - In the case of SC1 tip recirculation zones can increase EPL in the near injector region by 60%
    - Shoulders on the radial profiles are another indication of the recirculation zone
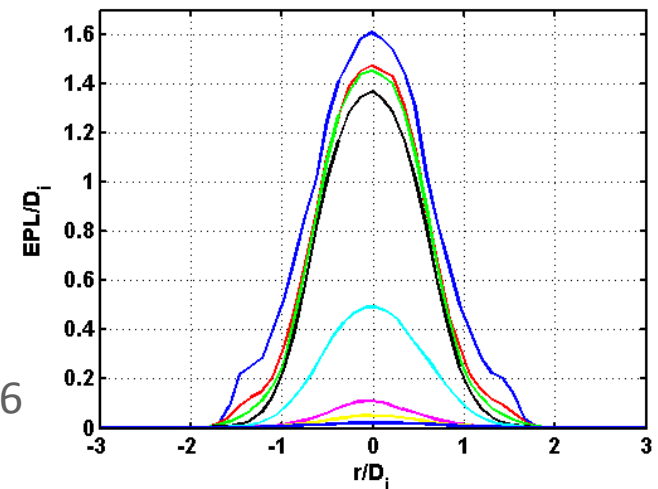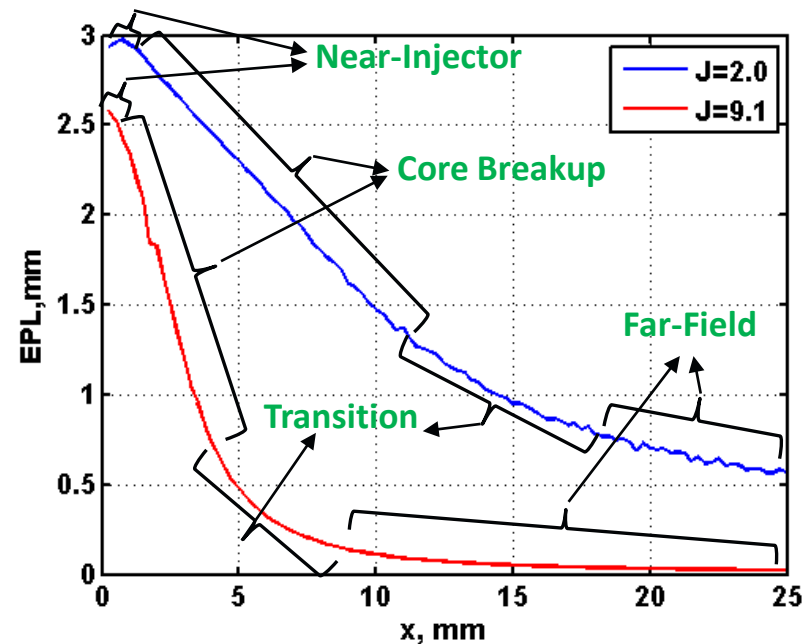

SC1

Φ =0.46

Φ =9.6

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12

Atomization Regions

- Centerline EPL profiles can be used to identify four unique spray regions
  - **Near-Injector Region:** Characterized by either a constant or slight increase in the centerline EPL following the injector exit
  - **Primary Atomization / Core Breakup Region:** Characterized by a nearly linear decline in EPL
  - **Transition Region:** Characterized by a clear change in slope in the centerline Profiles
  - **Far-Field Region:** Characterized by a continuing drop in EPL as the spray widens, secondary atomization decreases droplet size and droplet velocity continues to slowing increase
- Future work will use EPL profiles to quantitatively define these regions

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13

Mass Flux Ratio

- SC4 and SC24 have same inner jet geometry and same velocities for the three conditions
  - Difference in m is due to area ratio changes
  - m has minor effect in the near field
  - In the far field region lower m values results in more gas to liquid momentum transfer and therefore higher velocities and lower EPL
- SC1 geometry difficult to compare because of liquid in the recirculation zone
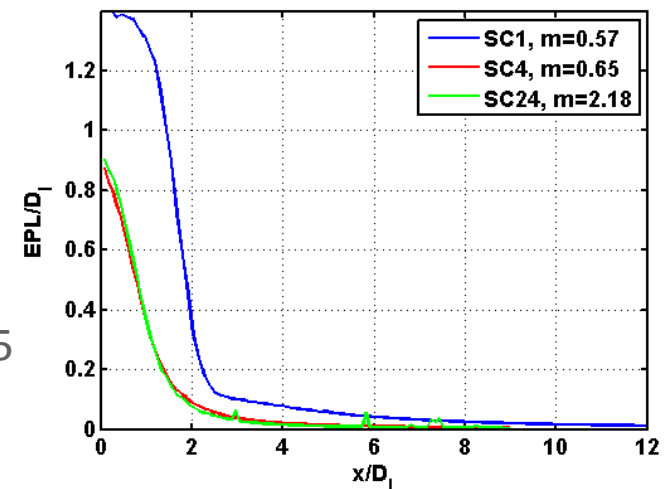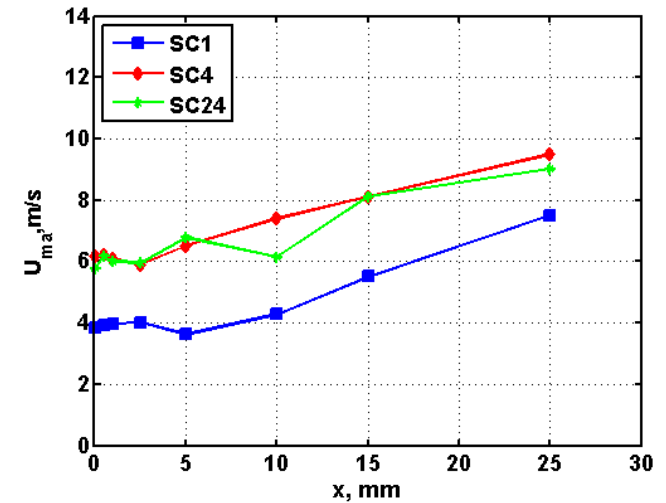

Φ=0.5

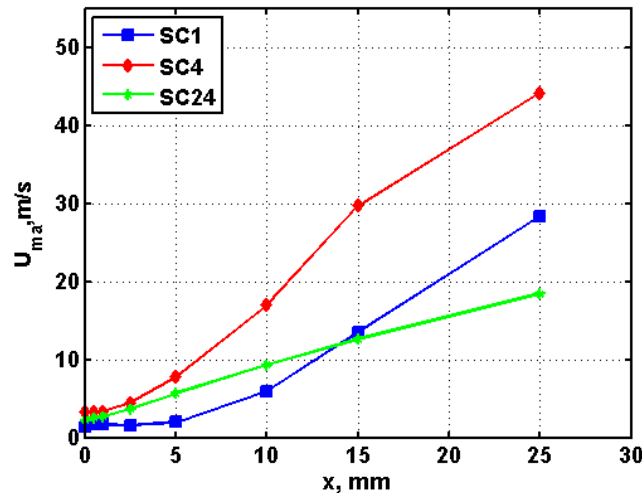Φ =2.0

SC1

SC4

Φ =15
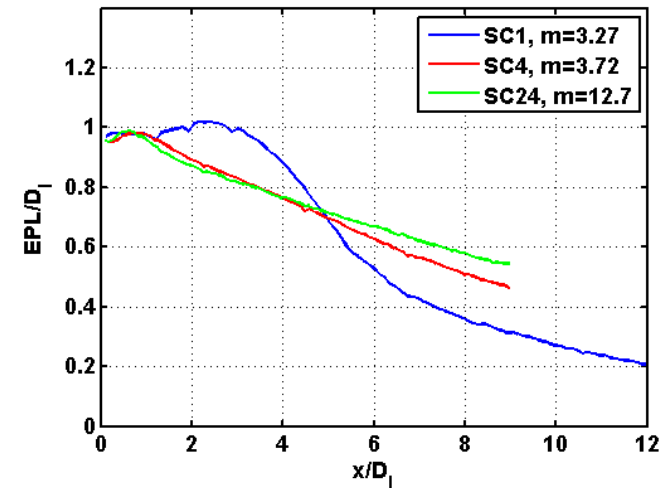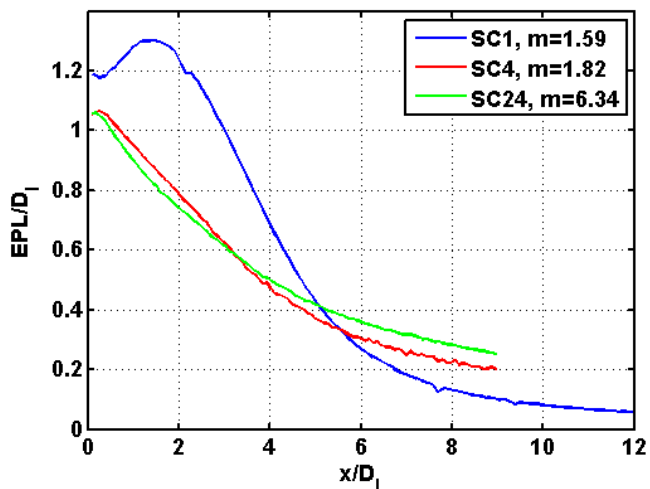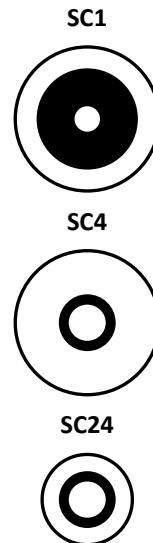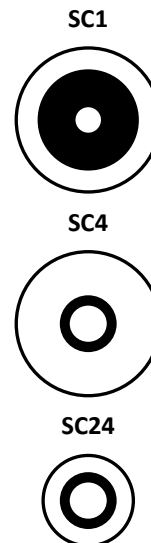
SC24

Mass Averaged Velocity

- Obtained by dividing liquid mass flow rate by the integral of the radial liquid density profile

- m can have a significant effect on the velocity in the far field

  – Comparing SC4 (m=0.84) and SC24 (m=2.83) for Φ=10; increase in m is sufficient to decrease U_{ma} from 23 m/s to 45 m/s

- Liquid mass in the recirculation zones of SC1 results in U_{ma} values below exit velocity
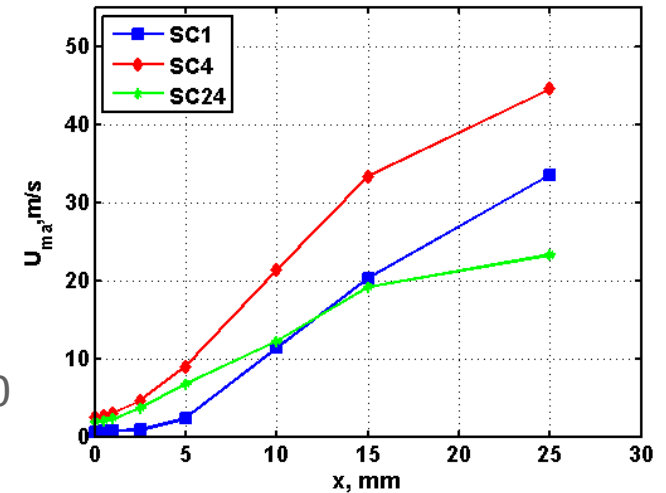

Φ=0.5

Φ =5.0

Φ =10

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15

Acceleration

- Accelerations can be calculated from the mass averaged velocities and the distance between radial points
  - Large uncertainty given the small distances, high velocities, and limited number of points available
  - Acceleration for SC4 peaks around 60,000 m/S^2 between 10 and 15 mm downstream (3.6-5.4D_i)
  - For SC4 and SC24 acceleration appears to decrease after 15 mm(5.4D_i) downstream

Φ =5.0

Φ =10

SC1

SC4

SC24
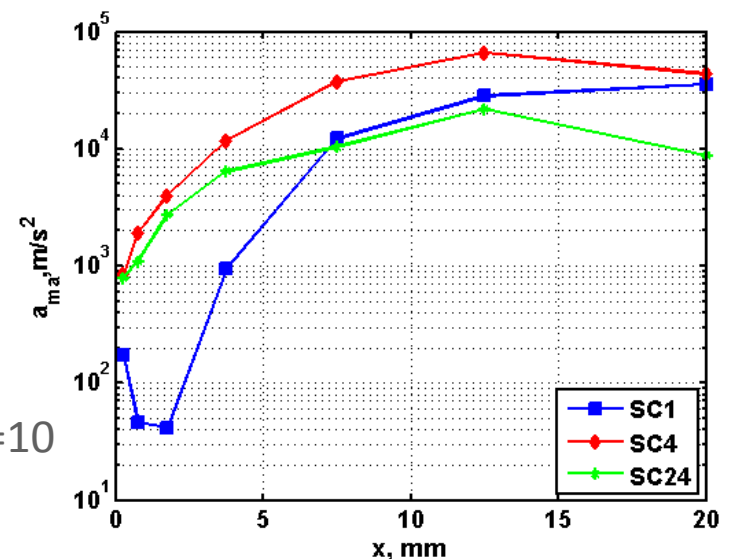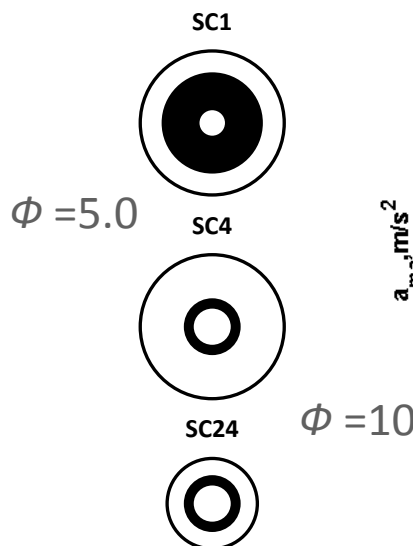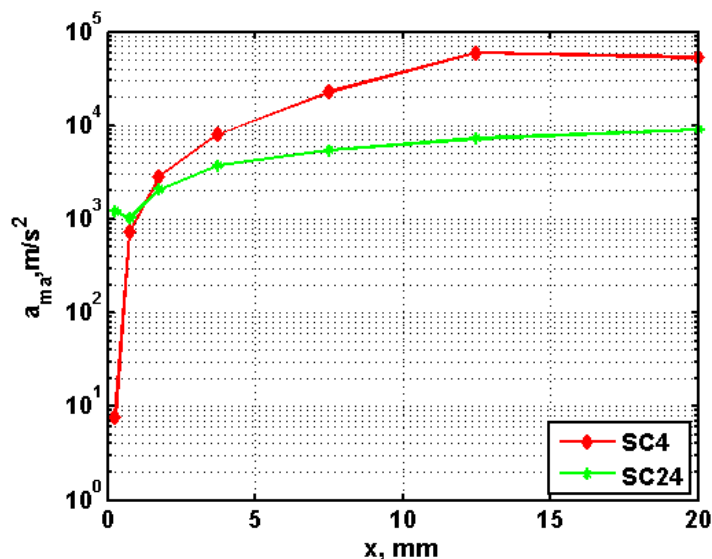
Summary & Conclusions

- X-ray radiography was used to quantitatively examine shear coaxial jet injectors
  - First quantitative measurement of the mass density in the near injector region of this injector type
  - Radial profiles were made as close as 0.02 mm from the injector exit
- Centerline EPL profiles showed same general trend with Φ reported in studies of the dark core length
  - Shortening of the core region with increasing Φ
- For thin post lip injectors (SC4 and SC24) peak EPL was found to vary ± 6% from D_i
- Both radial and centerline measurements indicated substantial liquid mass in the tip recirculation zone of the thick post injector SC1
- Centerline EPL profiles can be used to identify four unique spray regions: Near-Injector, Primary Atomization / Core Breakup, Transition, and Far-Field Region.

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Summary & Conclusions

- The mass flux ratio has a minor effect in the near-field and in the far-field region lower m values result in more gas to liquid momentum transfer and , therefore, higher average droplet velocities and lower EPL

- Mass averaged velocities were calculated from the radial EPL profiles and measured mass flow rates

  - Showed the significant effect the relative momentum between the two jets (m) can have on the average droplet velocity in the far-field region

- Future work will focus on using these quantitative measurements to further characterize spray regions and refine atomization models for this injector type

Acknowledgements

- A portion of this research was performed at the 7-BM beamline of the Advanced Photon Source, Argonne National Laboratory. Use of the Advanced Photon Source at Argonne National Laboratory was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

- Special thanks for their assistance in setting up and data collection during the testing campaign at Argonne National Laboratory
  - Todd Newkirk (Jacobs Technology, Inc.)
  - Earl Thomas (ERC, Inc.)
  - Larry Villasmil (Rochester Institute of Technology)

7-BM